Observations on the Solar Particle Events of July 1961

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Abstract. The spectrum of solar protons with energies between 77.5 and 290 Mev has been measured during the flare event of July 12, 1961, by means of nuclear emulsions flown on a high-altitude balloon from Fort Churchill. The differential spectrums averaged over the period from 0839 to 1819 UT, July 13, are consistent with a power law of kinetic energy with an exponent $\gamma = 5.6 \pm 0.3$, a power law of total energy over rest energy with $\gamma = 47 \pm 3$, and an exponential law of rigidity with $P_0 = 52 \pm 3$. The intensity of particles with $E \geq 77.5$ Mev $= 1.69 \pm 0.14$ p/cm² ster sec. During the solar particle event of July 18 the intensity of particles with $E \geq 100$ Mev was 40 ± 8 p/cm² ster sec in the time interval from 1305 to 1918 UT, July 18. The similarity between these events and those of April 29 and May 4, 1960, is noted.

Introduction

In July 1961 three high-altitude balloons carrying nuclear emulsions were flown from Fort Churchill, Canada. Both the second and third flights were made while large intensities of energetic particles associated with solar flares were arriving at the earth. In this paper we present the results of an analysis of the data obtained from these two flights on the proton intensities and spectrums.

A chronological history of some of the more relevant data is given in Figure 1. This figure shows, reading from the top: the absorption of cosmic noise in decibels recorded by the Churchill 30-Mc/s riometer; the heliographic longitudes of the major solar flares from McMath plage regions 6171 and 6172, together with an indication of their magnitudes [*National Bureau of Standards,* 1961]; the geomagnetic planetary 3-hour range indices K_p,[2] together with the times of occurrence of those sudden commencements (s.c.) observed by many stations [*Lincoln,* 1961, 1962]; the duration of each flight from time of stack flip to cut-down; and the counting rate of the Deep River neutron monitor (Carmichael, private communication, 1961).

From Figure 1 it can be seen that flight 1 was made during a time of quiet geophysical conditions. The results from this flight were used to correct for galactic cosmic ray background in the later flights. During flights 2 and 3, on the other hand, conditions were extremely disturbed, and major PCA events were in progress. Furthermore, during flight 3 an increase was recorded by sea level neutron monitors. The emulsions on this flight, being essentially saturated, have not provided detailed data.

Observations on July 13, 1961 (Flight 2)

Balloon flight. A stack of twenty-three 20 cm × 10 cm × 0.06 cm Ilford emulsions was flown on flight 2 under 0.1 g/cm² of packing material. The stack was oriented so that its short edge was vertical and was rotated through 180° at ceiling altitude. The time-altitude curve (Figure 2) shows that most of the flight from the time the stack was flipped to cut-down was spent under 4.1 grams of atmosphere. The residual atmospheric pressure was measured to within ±0.1 g/cm² by photographing a Wallace and Tiernan (0–20 mm of Hg) gauge.

Proton energy spectrums. A. From-ending particles: To get a preliminary determination of the energy spectrum of the solar protons, we measured the density of ending particles at several levels in the emulsions. We corrected the observed values for ending particles produced at other times and produced by the normal cosmic ray flux by subtracting the density of particles observed in flight 1, after allowing for the differing durations of the flights.

If the stack is assumed to be infinitely thick, so that the total material traversed at any

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[2] Notice K_p is a semilogarithmic quantity, and thus such a plot visually underemphasizes the changes in magnitude of magnetic disturbance.

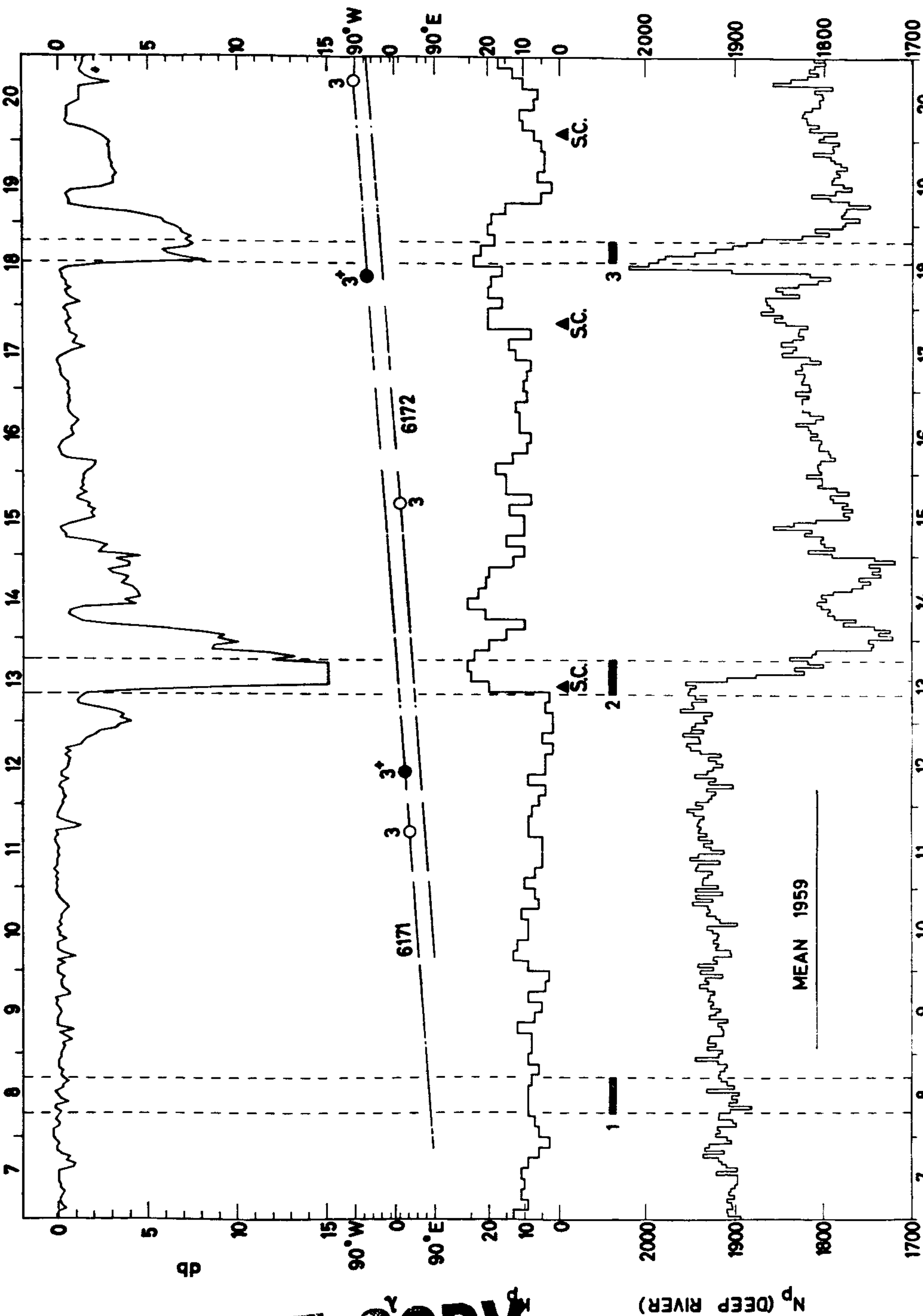

Fig. 1. Solar and geophysical data during July 1961. From top to bottom are shown: absorption of 30-Mc/s riometer, Fort Churchill; solar flares; magnetic K_p index; sudden commencements; balloon flights; and neutron monitor counting rate, Deep River.

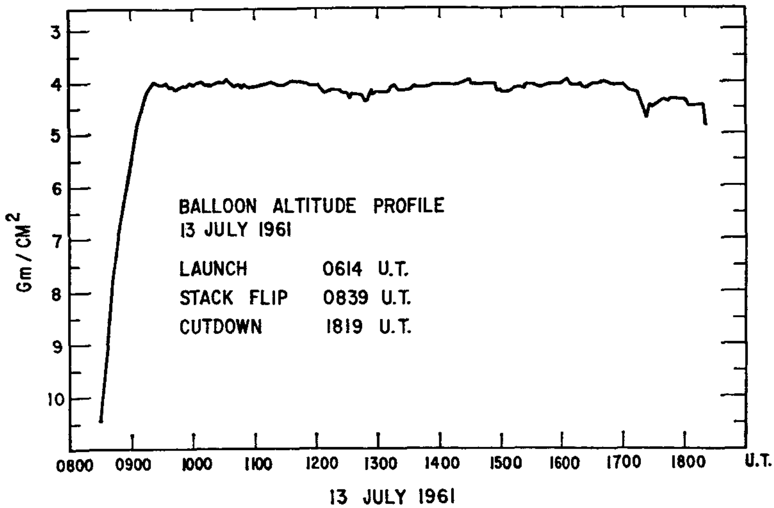

Fig. 2. Balloon flight profile, flight 2.

zenith angle θ at a vertical depth below the top of the atmosphere R_1 is given by $R_1 \sec \theta$, and, if the primary particles obey a differential energy spectrum of the form $dN = CE^{-\gamma}\, dE$, then the density of particles at a depth of R_1, ΔN_1, is related to the density at some other depth R_2 by (see appendix 1)

$$\frac{\Delta N_1}{\Delta N_2} = \left(\frac{R_2}{R_1}\right)^{n(\gamma-1)}$$

where n is the index of the range-energy relation. Then, if the stack is assumed to have been exposed under the equivalent of 16-mm emulsion, $\gamma = 6.3 \pm 0.4$ for $R_1 = 20$ mm, $R_2 = 30$ mm, and only 3.5 ± 0.5 for $R_1 = 30$ mm, $R_2 = 40$ mm. Obviously in this second case the assumption that the stack is infinitely thick was not justified, and an appreciable fraction of the particles reaching the emulsion level arrive from the sides and have lower primary energies than is assumed.

It should be appreciated that this method of analysis can only be valid, even for thick stacks, when the energy spectrum is steep, so that the majority of particles arrive from directions near the zenith; otherwise, it is not permissible to neglect the effects of the nuclear absorption of particles.

B. Integral and differential scans: To analyze the solar protons in more detail, we made integral scans at depths corresponding to proton energies at the top of the atmosphere of 77.5 and 98 Mev. Differential scans were made at depths corresponding to 90 and 110 Mev, the energy of each particle being determined either from its range or its ionization. To relate the differential intensities to those from the integral scans, the very small contribution from protons with $E > 290$ Mev was deduced by an extrapolation of the differential energy spectrum.

The intensities obtained from these scans were corrected for background, absorption in the overlying emulsion and atmosphere, and variations in altitude. The background correction was deduced from the energy spectrums of primary and secondary particles observed in flight 1. This contribution was 1 per cent or less for the integral scans and for the energy intervals less than 120 Mev, but rose to 50 per cent in the interval 200 to 290 Mev. We corrected for absorption by using absorption mean free paths of 40 cm in emulsion and 100 g/cm² in air. The correction for variation in flight altitude ranged from 4 per cent at 77.5 Mev to 1 per cent in the interval from 200 to 290 Mev. Because of the steep spectrum, no correction was necessary for the period before the stack was rotated other than the background correction noted above.

The resulting intensities are shown in Table 1. The integral intensity above 290 Mev was not measured, but was calculated from an extrapolation of the differential energy spectrum. The errors quoted are statistical plus systematic errors. The systematic error is about 5 per cent,

TABLE 1. Integral Proton Intensities for Flight 2

Proton Energy, Mev	Integral Intensity, p/cm² ster sec
77.5*	1.693 ± 0.14
90	0.856 ± 0.065
98*	0.600 ± 0.049
100	0.554 ± 0.050
110	0.338 ± 0.036
120	0.219 ± 0.030
140	0.109 ± 0.022
200	0.019 ± 0.010

* Independent integral points.

and arises primarily from the uncertainties in the acceptance solid angle and collecting area.

The resulting differential energy spectrums are shown in Figure 3. In the range of energies studied it is not possible to distinguish between a power law of kinetic energy, a power law of total energy, and an exponential rigidity spectrum, as can be seen from the figure. The following results were obtained for each.

Power law of kinetic energy

$$\frac{dN}{dE} = CE^{-\gamma} \qquad \gamma = 5.6 \pm 0.3$$

Power law of total energy

$$\frac{dN}{dE} = C\left(\frac{W}{W_0}\right)^{-\gamma} \qquad \gamma = 47 \pm 3$$

Exponential rigidity

$$\frac{dN}{dP} = Ce^{-P/P_0} \quad P_0 = 52 \pm 3$$

In an attempt to distinguish between these spectral forms, we plotted integral spectrums in Figure 4 together with the low-energy points obtained from counters on the Injun 1 satellite [*Maehlum and O'Brien*, 1962]. The point at 1.5 Mev (53-Mv rigidity) was plotted assuming that the differential intensity between 1.5 and 17 Mev was essentially the same as the integral intensity above 1.5 Mev. Figure 3 shows that an extrapolation of the exponential rigidity spectrum suggested by *Freier and Webber* [1963] fits the Injun 1 data most closely. However, the power law of total energy is not inconsistent with the point at 40 Mev, though it does not fit the point at 1.5 Mev. The power law of kinetic energy predicts much higher intensities than are observed at the lower energies.

Observations on July 18, 1961 (Flight 3)

A large stack of nuclear emulsions was flown on July 18, 1961. Originally intended to study the particle intensities very late in the event of July 12, the balloon was actually launched at a time that almost coincided with the 3⁺ flare that caused the solar particle event of July 18; it floated at a mean ceiling altitude of 2 g/cm² for a six-hour period when the 30-Mc/s polar riometer at Churchill was registering its maximum absorption for the event.

The electron-sensitive emulsions from this

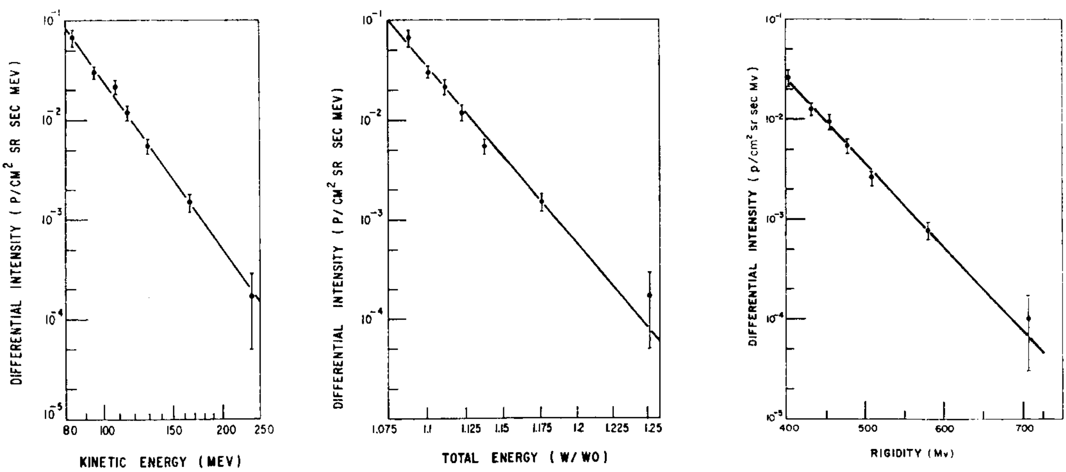

Fig. 3. Differential proton intensities versus kinetic energy (logarithmic scale), total energy/rest energy (logarithmic scale), and rigidity (linear scale).

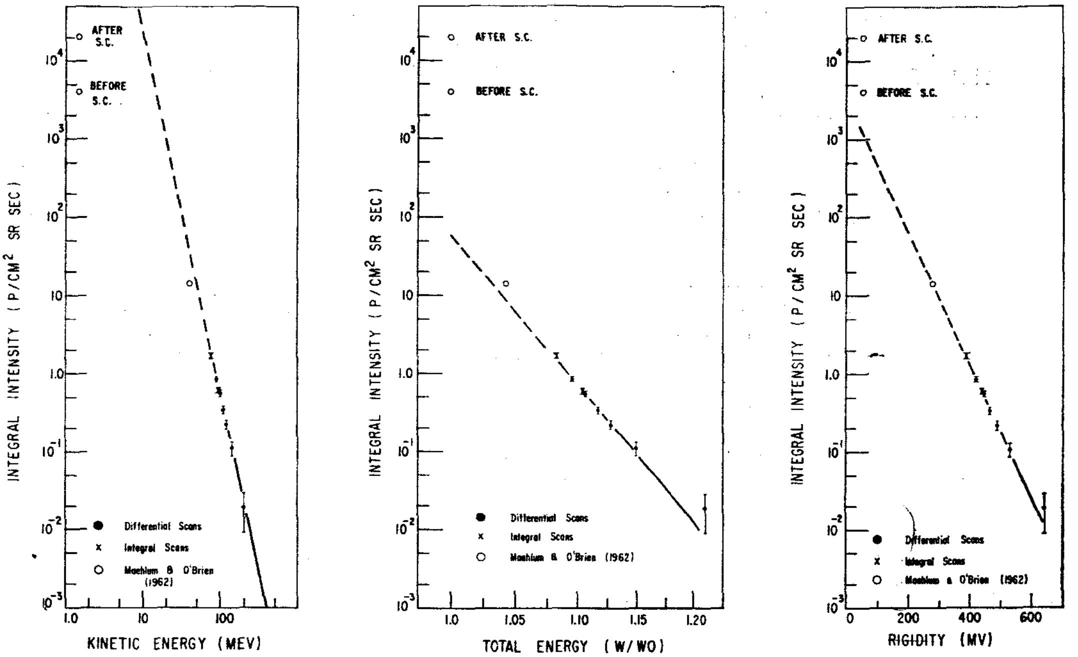

Fig. 4. Integral proton intensities versus kinetic energy (logarithmic scale), total energy/rest energy (logarithmic scale), and rigidity (linear scale).

flight were essentially saturated, and only an integral proton intensity at 100 Mev of 40 ± 8 p/cm² ster sec has been obtained. In the future the less sensitive emulsions in the stack will be used for a composition study of the low-energy solar particles.

Discussion

The spectrums. The spectrums obtained from the emulsion data of flight 2 are averaged over a ten-hour period; they have meaning only if the shapes of the spectrums did not change markedly during this time. In this period there was a sudden commencement at 1112 UT on July 13, and the 27.6-Mc/s riometer at College [*Leinbach*, 1962] showed an increase in absorption during the magnetic storm following the sudden commencement. Counter results from the State University of Iowa satellite Injun 1 [*Maehlum and O'Brien*, 1962] indicate that the increase of absorption at College can be explained by an increase in the intensity of particles below energies of 17 Mev combined with a decrease in the threshold rigidity at the latitude of the College riometer station. The integral flux of particles with kinetic energy greater than 40 Mev as measured by Injun 1 during the time of the balloon flight remained essentially constant, though there was a slight increase (about 20 per cent) after the sudden commencement. We would expect the particle intensities at higher energies to be affected even less. As a consequence, it is reasonable to assume that the intensity of particles with energies greater than 77.5 Mev was not markedly affected by the sudden commencement and magnetic storm, and that the spectrums obtained here are meaningful averages for the time period 0839 to 1819 UT, July 13.

For the event of July 18, the emulsion data consist only of an integral point at 100 Mev. The Injun 1 data [*Maehlum and O'Brien*, 1962] show that, during the time of the flight, 1305 to 1918 UT on July 18, the integral intensity of particles above 40 Mev was going through a broad maximum, increasing from 3×10^2 to 5×10^2 p/cm² ster sec. Also, the 30-Mc/s riometer at Churchill showed a sustained maximum absorption of 7 to 8 db. This would indicate that the particle intensities were not changing rapidly during the flight period and that the integral flux value obtained is a reasonable average value.

TABLE 2. Comparison of the Events of July 1961 and April, May 1960

1615 UT, July 11	Class 3 flare, S6E32; small PCA	before 0130 UT, April 28	Class 3 flare, S5E34; small PCA
1000 UT, July 12	Class 3^+ flare, S7E22; large, slowly developing PCA, steep solar proton spectrum	0138 UT, April 29	Class 2^+ flare, N12W20; large, slowly developing PCA, steep solar proton spectrum
1112 UT, July 13	Sudden commencement, Forbush decrease, rapid increase in absorption	0132 UT, April 30	Sudden commencement, Forbush decrease, rapid increase in absorption
≃0730 UT, July 14	Resurgence of magnetic storm	1213 UT, April 30	Sudden commencement, Forbush decrease
0920 UT, July 18	Class 3^+ flare, S8W60; neutron monitor increase, rapidly rising event, flat solar proton spectrum	before 1000 UT, May 4	Class 2 flare, N14W90; neutron monitor increase, rapidly rising event, flat solar proton spectrum
0247 UT, July 20	Sudden commencement, no Forbush decrease	≃1650 UT, May 6	Magnetic storm, no Forbush decrease

Flare times are taken from National Bureau of Standards CRPL-F Reports, Part B.
Sudden Commencement times are from J. Virginia Lincoln, Selected Geomagnetic and Solar Data, *J. Geophys. Res.*, *65*, 4195, 1960; and *67*, 381, 1962.

Comparison with the events of April 29 and May 4, 1960. As was discussed by *Maehlum and O'Brien* [1962], the spectrums for the two events at the time of maximum riometer absorption are significantly different. The event of July 12 has a very steep spectrum extending to energies well below 100 Mev, whereas the event of July 18 has a significantly flatter spectrum, particularly at energies less than 100 Mev.

The two events discussed here show a strong resemblance to the events of April 29 and May 4, 1960. In the event of April 29, 1960, the Explorer 7 counters indicated an omnidirectional flux for particles with energy >30 Mev of 18 p/cm^2 sec at about 0000 UT, April 30 [*Lin*, 1961]. At this time the 27.6-Mc/s riometer at Thule was showing absorption of about 8 db [*Leinbach*, 1962]. We must assume, to explain the large riometer absorption, that the spectrum for the April 29 event was quite steep and had a large number of particles with energies below 30 Mev. Hence, the shape of the energy spectrum must have resembled that of the July 12 event.

During the event of May 4, 1960, there was a neutron monitor increase of over 300 per cent at Deep River [*Carmichael and Steljes*, 1961], though the 27.6-Mc/s riometer at Thule showed a maximum absorption of only 5 db [*Leinbach*, 1962]. In addition, the spectrum measured between 1700 UT May 4 and 0200 UT May 5 by *Biswas and Freier* [1961] was very flat.

For each of these periods there was a flare followed by a small PCA event, a flare about a day later followed by a large PCA event and solar particle event characterized by a steep spectrum, followed in turn a few days later by a flare and solar particle event characterized by a flat spectrum. These and other similarities between the two events are summarized in Table 2. This indicates that conditions in the space between the sun and the earth and on the sun were very similar during April and May 1960 and July 1961 in those respects that are important in the production of accelerated particles and their transit to the earth. A more detailed intercomparison may indicate just which are the important conditions.

Appendix 1

Assume the incoming protons have a differential energy spectrum of the form

$$dN = -CE^{-\gamma}\, dE$$

then if R is the range of material traversed from the top of the atmosphere $E = aR^n$, where a and n are essentially constants over a reasonable spread of energies,

$$dN = -C(aR^n)^{-\gamma} anR^{n-1}\, dR$$

Now at one level in the emulsion the density of particles coming to rest, ΔN, is given by

$$\Delta N = \int_{R_1}^{R_{\max}} \sin \theta e^{-R/\lambda}\, dN$$

where R_1 is the vertical range, θ the zenith angle, and λ the absorption mean free path, so that

$$\Delta N = -Ca^{(1-\gamma)}n \int_{R_1}^{R_{\max}} \sin \theta R^{(n-1-n\gamma)} e^{-R/\lambda}\, dR$$

but $R = R_1 \sec \theta$, and so

$$\Delta N = -Ca^{(1-\gamma)}nR_1^{\,n(1-\gamma)} \cdot \int_0^{\pi/2} (\sec \theta)^{n(1-\gamma)} \tan \theta \sin \theta e^{-R_1 \sec \theta/\lambda}\, d\theta$$

Thus at two different levels with vertical ranges R_1 and R_2, *if* we can neglect the effects of nuclear absorption,

$$\frac{\Delta N_1}{\Delta N_2} = \left(\frac{R_2}{R_1}\right)^{n(\gamma-1)}$$

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